ULTRASONIC NONDESTRUCTIVE EVALUATION OF CRACKED COMPOSITE LAMINATES

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INTRODUCTION

The use of guided waves in the ultrasonic nondestructive evaluation of structural components, e.g., bonded plates and composite laminates, has received considerable attention in recent years. Highly accurate and efficient experimental techniques have been developed to generate, record and analyze these waves in laboratory specimens, leading to an improved capability in flaw detection and material characterization in a variety of materials [1-4]. A convenient method to generate guided waves in a plate or laminate is the so-called leaky Lamb wave (LLW) technique. It has been demonstrated in several recent papers [5-7] that phase velocity and amplitude of guided waves composite laminates can be determined very accurately in a broad range of frequencies and velocities by the LLW technique.

The main objective of the research presented here is to simulate the LLW experiment in an effort to develop a nondestructive method for the material characterization and damage evaluation of composite laminates. In order to validate the theoretical model of composite, the reflected field from a composite laminate immersed in water and obliquely insonified by an acoustic beam is calculated and compared with laboratory data. The specimens can be either unidirectional or multi-orientation undamaged laminates of arbitrary thickness. Both time harmonic and transient waves are considered.

After model validation, the phase velocities of free and leaky guided waves in both unidirectional and multi-orientation laminated composites are studied and compared with LLW data to determine their stiffness constants. Finally, the wave behavior in a unidirectional composite containing a delamination and in a multi-orientation laminate permeated by a number of small transverse cracks. The depth of the delamination is determined from the amplitude spectra of the reflection coefficients. A systematic inversion scheme is used to determine the stiffness degradation of damaged laminates containing transverse matrix cracks.

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THEORY

Fiber-reinforced composite materials are heterogeneous and composed of at least two phases. A large number of parallel, cylindrical fibers embedded in the matrix introduces an axial symmetry in the effective elastic property of the material. It is reasonable to assume that the material is elastically transversely isotropic and homogeneous in its overall static behavior. The laminates are assumed to be uniform transversely isotropic plates with symmetry axis parallel to the surfaces of the plates. The resin layers between two adjacent laminae can be modeled by isotropic viscoelastic layers, but they are ignored in the calculations here.

We consider a fiber-reinforced composite plate immersed in water and insonified by a plane harmonic acoustic wave (Fig. 1). We wish to calculate the reflected field as a function of frequency and angle of incidence. The detailed formulation is described in [8], and will not be repeated here.

The basic idea behind the inversion is data fitting to theoretical models. A major difficulty in inversion is that it requires the solution of a system of nonlinear equations, resulting in non-uniqueness [9]. In this study, a least squares method for the nonlinear, implicit model presented by Britt and Luecke [10] is applied to estimate the material properties of damaged composite laminates.

The minima in the amplitude spectra of the reflection coefficient Δ correspond to the modal frequencies of dispersive guided waves in the laminate. The reflection coefficients are complex-valued functions of frequency, laminate thickness as well as the material properties of the composite and the surrounding fluid. Let Δ be expressed as

$$\Delta = \Delta_R + i\Delta_I \tag{1}$$

where Δ_R is a smooth function. The modal frequencies of both free and leaky guided waves are almost identical in a broad frequency range. The real part of (1) is related to the dispersive guided waves and the imaginary part is contributed by the influence of water loading. Δ_I is approximately zero at the modal frequencies because of small influence of water loading, and dispersive guided waves are excited at the frequencies where Δ_R vanishes. The dispersive guided waves satisfy a system of equations that corresponds to the phase velocity or the angle of incidence of the form

$$\Delta_R = G(\mathbf{f}, \mathbf{v}, \mathbf{C}) \approx 0 \tag{2}$$

where $\mathbf{f}$ is the vector of modal frequencies, $\mathbf{v}$ is the vector of phase velocities and $\mathbf{C}$ is the vector of stiffness constants, C_{ij}.

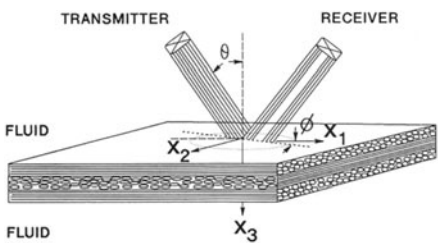

Fig.1 Schematic diagram of the LLW experiment

The thickness of each lamina, mass densities of specimen and surrounding fluid, and acoustic wave speed are assumed to be constant. The objective of inversion is to find a set of maximum likelihood estimation of C_{ij} which satisfies (2) and minimizes the root-mean-squares (RMS) of the errors between the modal frequencies obtained from (2) and from measured data. It is not possible to solve this inversion problem (2) directly since Δ_R is a strong nonlinear function of the unknowns. An iterative procedure is necessary in seeking a convergent solution of (2) until $|f_{n+1} - f_n|$ and $|C_{n+1} - C_n|$ satisfy a convergence criterion.

In most recursive problems, the convergence speed of the solution is significantly affected by the initial guess. Deming's approximation [11] provides a convenient initial guess for the above iterative process. Furthermore, the accuracy of the derivatives of the objective function has a strong influence on the convergence. For general multidirectional laminated composites, the derivatives of the reflection coefficient function is extremely complex, and it is difficult if not impossible to obtain them analytically. A central difference method is used to approximate the first derivatives of G with respect to frequencies and material properties.

RESULTS AND DISCUSSION

Undamaged laminates

The laminated composites made of graphite/epoxy material are used as examples in the calculation. The fiber-reinforced laminates are modeled by a stack of transversely isotropic layers with the symmetry axis parallel to the interfaces in the absence of other inhomogeneities and defects. The elastic properties of graphite/epoxy used in the following calculations are given in Table 1, unless otherwise noted. In the experiments, the incident pulses were generated by a transducer of center frequency 5 MHz.

The numerical calculations are carried out for both time harmonic and transient waves. In the time harmonic case, the potential function, Φ_0, of incident wave is given by

$$\Phi_0 = e^{i(\xi_1 x_1+\xi_2 x_2+\zeta_0 x_3-\omega t)} \tag{3}$$

where $\xi_1 = k_0 \sin\theta \cos\phi$, $\xi_2 = k_0 \sin\theta \sin\phi$, $\zeta_0 = k_0 \cos\theta$, $k_0 = \omega/\alpha_0$, and α_0 is the acoustic wave speed of the surrounding fluid. In the transient case, with a given incident pulse, the time harmonic solution is multiplied by the Fourier transform of the incident pulse and the result is inverted by means of the fast Fourier transform (FFT). In calculating the total reflected time histories from the specimens, energy dissipation has been included to reduce the duration of motion.

The measured and calculated reflected signals from a 1 mm thick graphite/epoxy laminate specimen, AS4/3501-6 $[0]_8$, are shown in Fig. 2, and these for a typical composite laminate, a cross-ply $[0/90]_{2S}$ of 1 mm

Table 1. Material properties of the graphite/epoxy composite.

ρ (g/cm^3)	C_{11} (Gpa)	C_{12} (Gpa)	C_{22} (Gpa)	C_{23} (Gpa)	C_{55} (Gpa)
1.578	160.73	6.44	13.92	6.92	7.07

total thickness, are shown in Fig. 3. The figures indicate that the major shapes of the reflected signals are almost identical in the measured and calculated results. The calculated reflected pulses are in excellent agreement with the measured data at 0° and 45° orientations and in fair agreement at 90° to the fibers of top lamina.

The calculated dispersion curves of free guided waves in the cross-ply laminate are compared with the measured LLW data in Fig. 4. In order to cover this frequency range, the measurements were carried out by means of four transducers with overlapping frequency responses (1, 2.25, 5 and 10 MHz center frequencies). The LLW data in the overlapping regions of the frequencies were found to be slightly different, but were within the acceptable accuracy of 4%. The comparison was carried out in the lower frequency range of 0.1 - 5 MHz, due to the fact that the data within this range are more reliable. The agreement between measured and calculated results in this range is found to be very good.

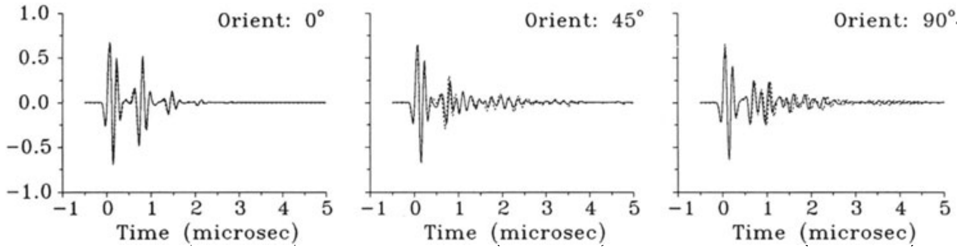

Fig.2 LLW time histories for a 1 mm thick $[0]_8$ laminate. The angle of incidence is 15°. Calaculated - solid curves, measured - dashed curves.

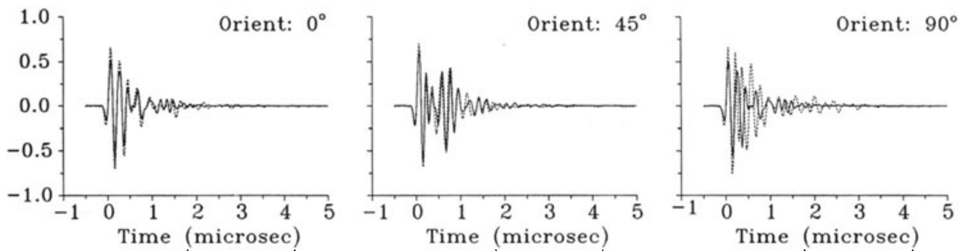

Fig.3 Same as in Fig.2, but for a 1 mm thick $[0/90]_{2s}$ laminate.

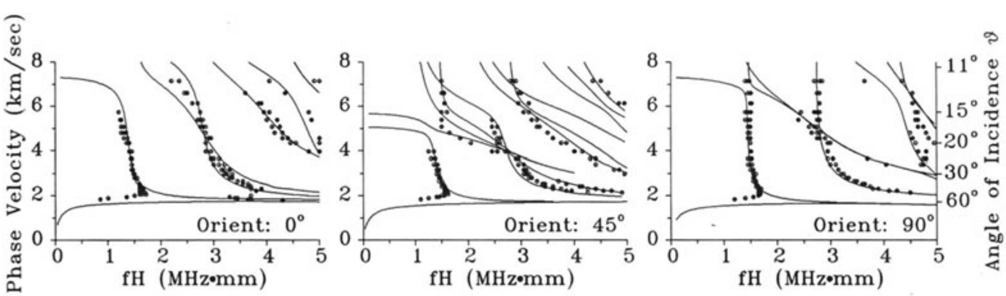

Fig.4 Comparison of calculated dispersion curves (line) for leaky Lamb waves with the LLW measured data (⊙) for a 1 mm thick $[0/90]_{2s}$.

DAMAGED LAMINATES

Delamination

One simple application of the LLW technique is to detect the depth and geometry of delaminations in composite laminates. The internal surfaces of the delamination are assumed to be free of traction. Neglecting edge effects, the plate thickness within the area of delamination is less than the total plate thickness. For a homogeneous plate, the products of the modal frequencies of the leaky Lamb waves and the plate thickness are a set of constants. Let f_i^0 ($i = 1, \ldots, n$) be the modal frequencies, h^0 be the thickness of defect-free specimen, f_i^d ($i = 1, \ldots, m$, $m \leq n$) the modal frequencies for delaminated specimen and h^d the depth of delamination. Then the relations

$$f_i^0 h^0 = f_i^d h^d, \quad i = 1, \ldots, m. \tag{4}$$

hold approximately. Hence the depth of delamination can be determined from the averaged formula,

$$h^d = \frac{h^0}{m} \sum_{i=1}^{m} \frac{f_i^0}{f_i^d} \tag{5}$$

By comparing the position of the minima in the reflected spectra, two specimens of 0.15 inch thick graphite/epoxy $[0]_{24}$ composite plates were inspected. One is free of defects, another contains a delamination of about 1 in^2 at the interface between the 11th and 12th laminae. The measured and calculated results for 0° orientation at 20° angles of incidence are compared in Fig. 5. The geometry of the internal delamination can be determined by xy-scanning over the surface of the plate. The wave field is quite complex near the edges of of delamination because of wave diffraction. Since wave lengths in the composite plate are much smaller than the size of the delamination, the region affected by wave diffraction is small, and the resulting error is negligible.

The amplitude of the reflected spectra for the delaminated specimen is found to be higher than that for the defect-free specimen. The reason is, obviously, that the wave energy carried by the reflected signals from the defect-free specimen is less than that reflected by the delamination. However, the difference in the amplitudes can not be accurately predicted by the present analysis.

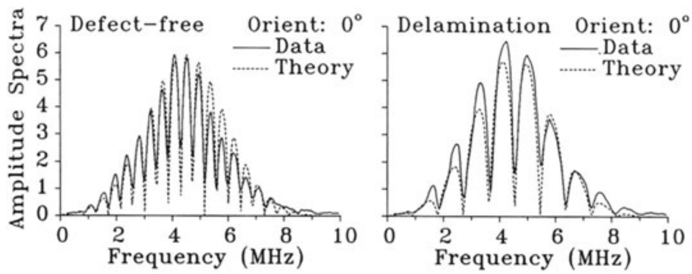

Fig.5 Reflected spectra for a 0.15" thick $[0]_{24}$ specimen at 20° angle of incidence. One specimen is free of defect, another contains interface-delamination between the 11th-12th lamina.

Transverse cracks

It has been found that a composite laminate permeated by a number of transverse cracks can still support a certain amount of loading, since these flaws are not through-the-thickness. Even though certain transverse cracks extend through the damaged lamina after saturation, the growth of the cracks is constrained by the adjacent plies of different fiber orientations. Thus, the overall stiffness of the laminate is reduced but does not vanish [12-14].

An investigation of damaged graphite/epoxy AS4/3501-6 cross-ply laminates is carried out. Two $[90/0]_{2S}$ specimens made up of the same materials are considered. One is a defect-free specimen, and the other is a damaged specimen containing transverse matrix cracks caused by fatigue loads of 60,000 cycles (at 10-41% of ultimate strength). The stiffness reduction in the damaged laminae is determined by a systematic inversion of low-frequency LLW data.

The mass density of each lamina is assumed not to be influenced by the presence of cracks. Certain engineering constants such as E_{22}, G_{12}, G_{23}, ν_{12} and ν_{23} of the cracked plies may change because of the appearance of the transverse cracks. In addition, the cracked plies are assumed to have lower elastic moduli than those of the defect-free laminae. The LLW data available here are only for 90° orientation to the fibers of the top lamina. It was indicated in [9] that only the stiffness constants C_{22} and C_{23} for a transversely isotropic solid can be determined through inversion of LLW dispersion data.

The cracked laminates are modeled as stacks of alternate defect-free laminae and degraded laminae with weak stiffness. The stiffness of defect-free laminae are kept as constants and used as the initial estimation of those for the cracked specimens. The material properties of the defect-free specimens, as given in the first row of Table 2, are inverted from the low frequency LLW data. For the alternate cracked laminae, the stiffness constants are assumed to be identical. The stiffness of the cracked specimen determined by the inversion scheme are given in Table 2. The measured LLW dispersion curves of fundamental modes are compared with the calculated results in Fig. 6. The corresponding engineering constants for the cracked plies are given in Table 3.

Table 2 Stiffness constants of the cracked and uncracked $[90/0]_{2S}$ laminate.

Damaged types	C_{11} (Gpa)	C_{12} (Gpa)	C_{22} (Gpa)	C_{23} (Gpa)	C_{55} (Gpa)
Defect-free	160.73	6.319	14.487	7.745	6.191
Fatigue	—	—	14.516	8.282	—

Table 3 Engineering constants corresponding to Table 2.

Damaged types	Thickness (mm)	E_{11} (GPa)	E_{22} (GPa)	G_{23} (GPa)	ν_{12}	ν_{23}
Defect-free	46.7×10^{-3}in	157.13	10.292	3.371	0.2842	0.5265
Fatigue	45.6×10^{-3}in	157.23	9.744	3.117	0.2772	0.5631

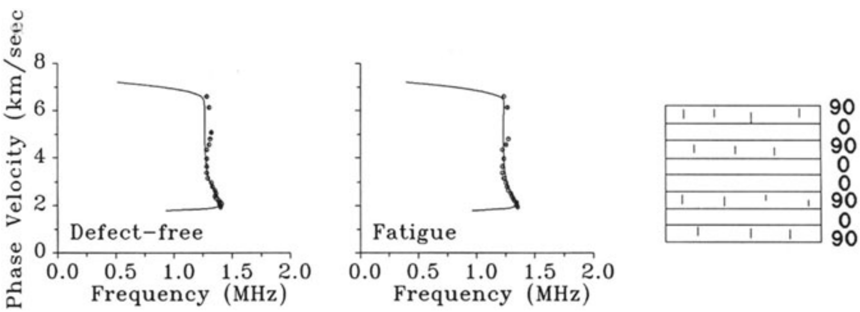

Fig.6 Fundamental leaky guided wave modes of the measurement (⊙) and for the material (line) inverted from LLW data.

CONCLUDING REMARKS

The theoretical model of the graphite/epoxy composite laminate consisting of a stack of transversely isotropic and dissipative laminae with symmetry axis of each lamina along the fiber direction appear to be able to predict acutually the wave behavior in real laminates observed in the LLW experiment.

The LLW technique combined with xy-scanning over the surface of specimens is an effective and accurate method to detect the depth and extent of interface delaminations in composite laminates. The reflected spectra for the delaminated specimens are found to be larger than those for defect-free specimens. The amplification can not be accurately predicted by the present analysis.

The low frequency modes of leaky guided waves are used to determine the stiffness reduction due to numerous small transverse cracks in the off-axis plies of multi-orientation laminates. In general, some of the overall engineering constants of undamaged as well as damaged laminates can be determined accurately through the inversion of low frequency LLW data.

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